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Final Report on

Investigating the influences of changes in convection types and boundary layer clouds on intraseasonal to interannual variations of precipitation over Amazon and on the tropical upper troposphere water vapor using ESE multi-satellite sensors

For the Period of January 2002 – December 2005

The Global Water and Energy Cycle Research Analysis

Office of Earth Sciences, National Aeronautics and Space Administration

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In this project, we addressed three major questions that are important for climate of the Amazon basin and water vapor, namely:

- How do changes in type of precipitation systems and associated circulation patterns, such as those associated with the easterly and westerly regimes observed during TRMM/LBA field program, contribute to seasonal and interannual variations of the Amazon rainfall?
- How do diurnal variation of the lower top clouds and surface heat fluxes affect precipitation systems in different large-scale wind regimes over Amazon?
- How do the different types of the convective/precipitation system affect water vapor in the upper troposphere and its climate feedbacks?

We tackled these scientific questions through the examination of an extensive collection of satellite data sets from TRMM (PR profiles and LIS), Aqua/Terra MODIS (clouds and aerosols), UARS MLS water vapor, and QuikSCAT, in conjunction with in situ ground-based observations from LBA (surface fluxes, radiosonde and tethered sounds, and S-pol rador), GEOS-1 and NCEP/NCAR reanalyses. The physical mechanisms responsible for the changes of clouds, vapor and precipitation were explored and their implications for theories and models addressed. In addition, a modeling approach was adopted using a regional climate model (RegCM3) to study the effects of biomass burning aerosols on the land surface processes and precipitation over Amazon during the transition season. Below are the summaries of our major findings.

1 Identified the role of cross-equatorial flow in intraseasonal forcing of convection and lightning activity in the Southern Amazon

Our previous works have established the relationship between the intraseasonal and interannual anomalous wet periods and northerly cross-equatorial low-level winds over the western Amazon (Wang and Fu, 2002). The South American Monsoon V-Index (VI) as a metric for detecting the precipitation variability over the Amazon Basin and sub-tropical South America was developed based on this relationship. Dr. Walter Petersen of University of Alabama at Huntsville leads the investigation of intraseasonal forcing of lightning and convective activity in the southern Amazon by stratifying the Brazilian Lightning Detection Network (BLDN) lightning data, TRMM LIS and PR data during the wet season of 1998-2001 according to this V-index (Petersen et al. 2005). Figure 1 shows the intraseasonal changes in convective structure (indicated by BLDN lightning data) as a function of VI regime (Figs. 1a-b). It is clear that intraseasonal variability in both the VI and BLDN CG flash counts is common, as indicated by the presence of periodic peaks and troughs in the anomaly values (anomalies relative to the monthly means).We found that the vertical structure properties of convection over the southern Amazon respond strongly to modulation of large-scale intraseasonal monsoon circulation change as measured by the magnitude of the V-index. In turn, convective vertical structure transitions result in marked differences in lightning activity and precipitation ice water path. Robust changes in precipitation ice water path diagnosed from the TRMM PR occurred coincident with changes in the VI and lightning amount, reinforcing hypotheses that mixed phase processes play a greater role in precipitation production during periods of southerly VI. The diurnal cycle of lightning flash rate (and by proxy, ice water path) was also modulated by the phase of the VI. For southerly VI phases, the diurnal cycle was strongly amplified in the late afternoon early evening hours, exhibiting an archetypical continental shape. For the northerly phase of the VI, the diurnal cycle of lightning still exhibited an afternoon peak, but was much weaker in amplitude (diurnal peak to trough) by a factor of four to five relative to the southerly phase.

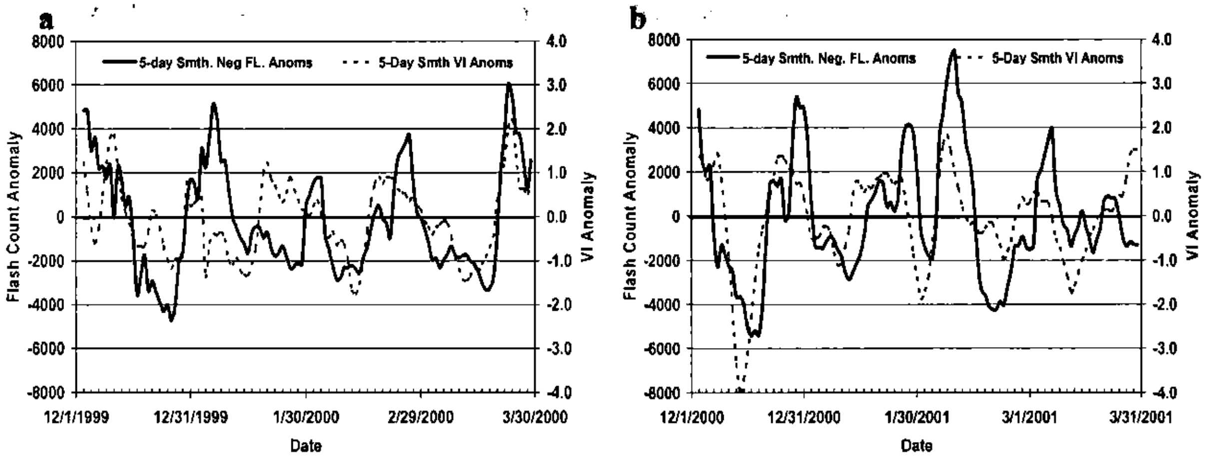

Figure 1. a) Five day running means of BLDN lightning flash count anomaly (left ordinate; solid line) and VI-anomaly (right ordinate; dashed line) for Dec. 1999- Mar. 2000. b) as in (a) but Dec.-Mar. 2000-2001.

2 Determined the influences of biomass burning on warm clouds and land-atmosphere interactions over the Amazon

The analysis of MODIS aerosol and warm cloud retrievals reveals the complex role of atmospheric dynamics and thermodynamics in regulating the influences of aerosols on clouds (Yu et al. 2005). For example, In a normal year 2003, the dominant effect is decreased cloud effective radius and increased cloud fraction. These terms add to the aerosol extinction and amplify the cooling at the surface and the top of the atmosphere (TOA). However, in an ENSO year 2002, smoke absorption reduces the cloud fraction and lowers the cloud-top height. The resultant warming offsets the increased reflection of solar radiation by the aerosols both at the surface and at TOA. Figure 2 top panel shows the calculated instantaneous solar forcing by biomass smoke. In 2003, the TOA solar fluxes were reduced by more than 50 Wm^{-2}, from both the aerosol extinction and from the increased cloud fraction and optical depth. By comparison, the increase of TOA fluxes from the reduced cloudiness in 2002 compensated the TOA cooling due to aerosol extinction, resulting in only a small net cooling for moderate smoke (AOD = 0.55) and nearly no net effect for heavy smoke (AOD = 0.95). In both years, the strong smoke absorption cools the surface substantially, with a cooling greater by -30 ~ -40 Wm^{-2} in 2003 than in 2002. For an AOD of 0.55 and 0.95 respectively, the percentage of the surface solar flux reduction due to smoke effects is about 23-29% and 36-43%, assuming AOD=0.1 for non smoke conditions. Correspondingly, the atmospheric heating due to smoke absorption increases by about 51-57% and 80-90% for moderate and heavy smoke conditions respectively. For the 24-hour average smoke forcing (bottom panel of Figure 2), the surface cooling in 2003 was 10~25 Wm^{-2} stronger than that in 2002. Our estimate of indirect forcing by smoke may be an underestimate because of its use of cloud-top retrievals by MODIS that could underestimate the broadness of droplet spectra in the cloud layers *[Matsui et al., 2004]*. In summary, the changes in radiative fluxes between such years would contribute to interannual changes of surface energy and water fluxes and radiative balance at the top of the atmosphere, probably also to variability of the wet season onset in the basin.

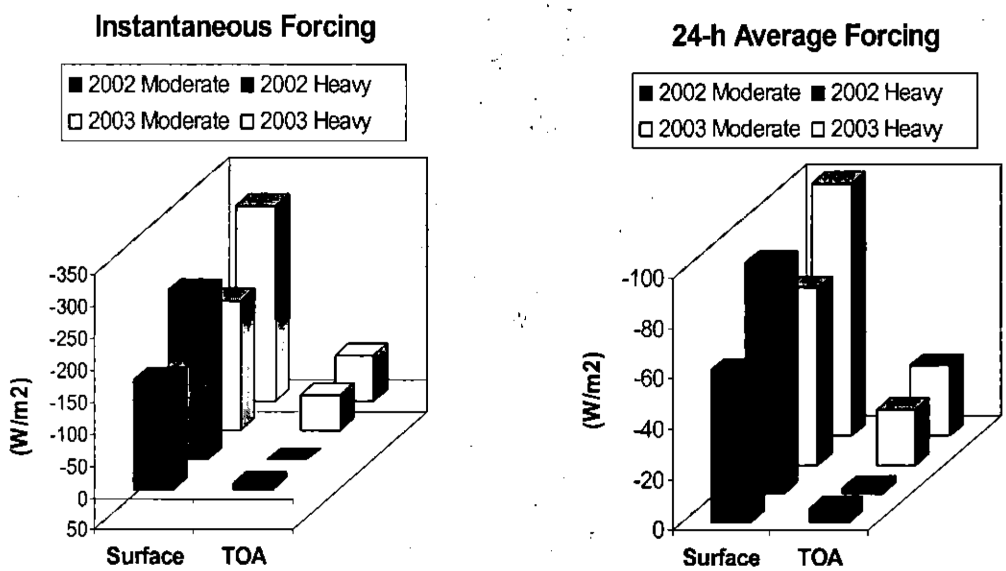

Figure 2. Smoke-induced solar radiative forcing at the top of atmosphere (TOA) and at the surface for moderate (AOD=0.55) and heavy (AOD=0.95) smoke conditions based on MODIS characterization of aerosol and cloud. The calculated values are the sum of direct, semi-direct, and indirect forcing. Clear-sky and cloudy-sky fluxes are calculated separately and then weighted by clear-sky fraction and cloudy-sky fraction to derive average fluxes. For cloudy-sky calculations, the same amount of aerosol as in the clear-sky is assumed to present beneath the cloud layer. AOD=0.1 is assumed to represent a background condition that is used as a reference for deriving aerosol forcing.

We have also performed regional modeling study on the influences of biomass burning on land-atmosphere interactions and dry-to-wet transition over Amazon (Yan Zhang 2005). The model results show that semi-direct effect of biomass burning aerosols is highly sensitive to the vertical distribution of aerosol. The main results from model are:

- Biomass burning aerosol scattering and absorption reduce the surface fluxes greatly.
- The cloud burning effect mainly occurs at noon and afternoon due to a diurnal maximum absorption of aerosol.
- The enhancement of the incoming solar radiation resulting from such cloud depletion

could compensate the reduction of solar radiation due to aerosol extinction.

- The reduction of the incoming solar radiation is mainly balanced by the reduction of sensible heat.
- Higher distribution of smoke aerosol inhibits the diurnal development of the boundary layer.
- Biomass burning aerosol could increase convective rainfall from 5% to 12% depending on aerosol vertical distribution. However, it has no significant effect on large scale rainfall.

Together, these results support the notion that the biomass burning smoke plays a large role in invoking different smoke-cloud process under different meteorological settings. The radiative perturbations by smoke as, i.e., a reduction of 20% to 40% of the surface solar flux compared to those of unpolluted condition, could significantly modify the wet season onset in ways not yet examined. This, in turn, has important implications for the distribution of aerosols and how it is represented in models.

3 Studied the influence of convective type on upper tropospheric humidity

We explored the influence of convective types (continental vs maritime) on upper tropospheric humidity (UTH), by analyzing Precipitation Radar (PR) and Ligtning Imaging Sensor (LIS) data from the Tropical Rainfall Measuring Mission (TRMM) in conjunction with HALOE and Microwave Limb Sounder (MLS) vertical water vapor profiles (Jonathon et al. 2003). An examination of TRMM-LIS lightning flash densities further confirms that the strongest convection is taking place over the continental regions, while maritime convection is relatively weak (Figure 3).

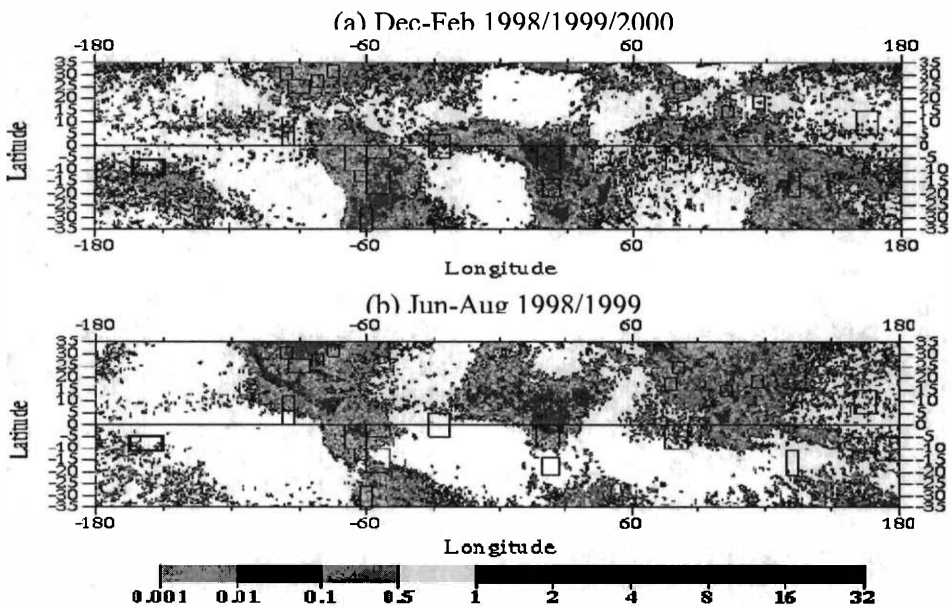

Figure 3. TRMM-LIS lightning flash density

Our results indicate that convective type plays an important role in determining the hemispheric summer UTH distribution. Tropical continental convection appears to be linked to the most humid UT, while tropical maritime convection is characterized by weaker vertical motion and higher convective precipitation than tropical continental convection, leading to a lower UTH over isolated oceanic regions. Although subtropical continental regimes experience deeper and stronger convection, they appear to be collocated with a drier UT than tropical regimes.

4 Examined relationships between the vertical structure of deep convection and upper tropospheric humidity

Previous studies of convective detrainment into the tropical UT have fallen into three major categories: in situ studies, which rely on very localized measurements in space and time; modeling studies, which cannot feasibly represent the totality of natural processes; and satellite studies, which have been limited until recently by inadequate spatial and temporal resolutions, as well as a general inability to discover convective vertical structure. Recent satellite technology has begun to address these problems, however, and we use the body of previous work as the basis from which to embark upon an observationally based, large-scale study of the evolution of convective detrainment into the tropical UT.

We begin by identifying tropical deep convective events within the TRMM Precipitation Radar (PR) volumetric radar reflectivities (Jonathon et al. 2004). We scan the area between 15°S and 15°N for radar reflectivities of 20 dBZ or greater at altitudes of 10 km or greater. These locations in space and time are then used to initialize a five day integration of the Goddard Space Flight Center Fast Trajectory model (Schoeberl and Morris, 2000). Horizontal and vertical motions are estimated along the trajectory path using diabatic calculations and winds from the National Centers for Environmental Prediction (NCEP) reanalysis project. To connect convective detrainment with downstream water vapor, we then scan the Atmospheric Infrared Sounder (AIRS) water vapor observations for temporal and spatial coincidence. We scan only those measurements taken within the 30 minutes following trajectory passage, and we consider a spatial match achieved if one or more valid AIRS observations falls within a 1° x 1° box centered on the trajectory point. If the matching criteria result in multiple matches for a single trajectory point, we use the mean water vapor of all matched AIRS observations. Data are linearly interpolated from the AIRS standard pressure levels to match the trajectory pressure.

Figure 4 shows the probability density functions (PDFs) for the TRMM PR reflectivity and AIRS water vapor 300 hPa mixing ratio matched on day1 (Figure 4a) and day 5 (Figure 4b) of the trajectory. It appears that stronger convection seems to detrain drier air and detrainment form higher reflectivities appears to dehydrate more quickly.

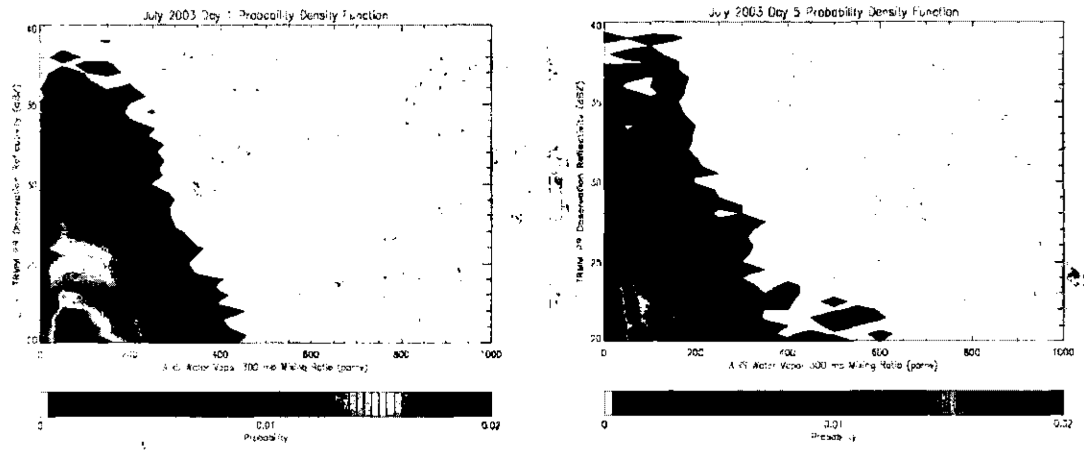

Figure 4. Probability density functions (PDFs) of TRMM PR observation reflectivity and Airs water vapor 300 hPa mixing ratio for July 2003.

While we are pleased with the early results of this experiment, we also recognize the potential for expanding and refining this study. We intend to also examine the MODIS dataset for any retrieval that collocate in space and time with the TRMM observations of deep convection that initialize our method. In this way, we will be able to supplement our knowledge of the convective structure with MODIS observations of cloud particle size distributions and cloud top heights.

Journal Publications and Conference Presentations

Peterson, W.A., R.Fu, R. Blakeslee, and M. Chen, Intraseasonal forcing of convection and lightning activity in the Southern Amazon as function of cross-equatorial flow, to be submitted to JGR, 2005.

Yu, Hongbin, R. Fu, R.E. Dickinson, Yan Zhang, M. Chen, and H. Wang, Influences of smoke on warm clouds over the Amazon as inferred from MODIS retrievals and their interactions with dynamics and thermodynamics, *J. Geophys. Res.*, submitted, 2005

Wang, H., and R. Fu, Cross-equatorial flow and seasonal cycle of precipitation over South America, *J. Climate*, 2002

Wright J., R. Fu, M. Chen, W. Petersen, Potential applications of Aura MLS to determining the influences of convective type on upper tropospheric humidity, AGU Fall meeting, San Francisco, December 8-12, 2003.

Wright J., R. Fu, and A. Dessler, Examining relationships between the vertical structure of deep convection and upper tropospheric humidity using AIRS, AIRS science meeting, Oct. 2004

Yan Zhang, Influences of biomass burning on land-atmosphere interactions and dry-to-wet transition over Amazonia, Research Paper, Georgia Tech, 2005.